Space Vector Pulse-Width Modulation for Multilevel Multiphase Voltage-Source Converters

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9 January 2009

Dissertation submitted for the degree of
European Doctor of Philosophy in Electrical Engineering

Outline

Outline

Multilevel Multiphase Motor Drives

Multilevel converters have:

- High voltage capability with voltage limited devices.
- Low harmonic distortion.
- Reduced switching losses.
- Increased efficiency.
- Good electromagnetic compatibility.

Multiphase machines have:

- Higher efficiency.
- Improved reliability and greater fault tolerance.
- Higher torque density and reduced torque pulsations.
- Lower per phase power handling requirements.

Multilevel multiphase motor drives combine
the benefits of both technologies.

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Space Vector PWM

Space vector PWM problem

	Two-level SVPWM	Multilevel SVPWM
Three phase	Well studied	Solved
Multiphase	Partially solved[1]	Not solved[2]

[1] Solved for five, seven and nine phases.

[2] Classical graphical tools become cumbersome in multiphase systems.

Objectives

Solve the multilevel multiphase SVPWM problem:

- Standard multilevel topologies.
- Any number of levels.
- Any number of phases.
- Low computational cost.
- Online hardware implementation.

Outline

Switching State Redundancy

Capability of power converters to produce the same output voltage with different switching states:

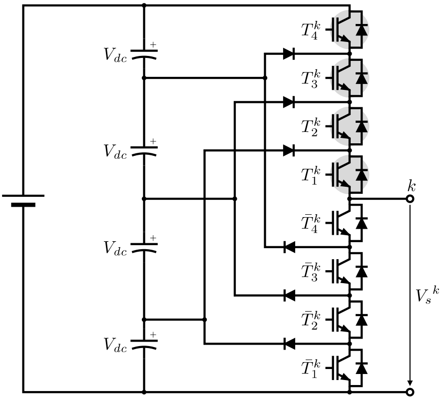
Joint-phase redundancy

- Refers to all phases
- Same phase-to-phase voltage
- Only in converters with floating neutral

Per-phase redundancy

- Refers to one phase
- Same phase-to-neutral voltage
- Only in some multilevel topologies

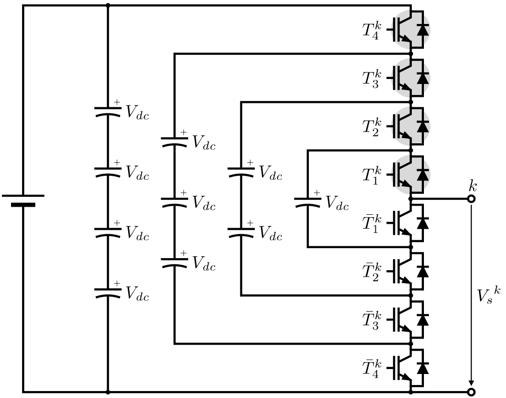
Diode-Clamped Converter



Five-level converter

T_1^k	T_2^k	T_3^k	T_4^k	${V_s}^k$	${v_s}^k$
0	0	0	0	0	0
1	0	0	0	V_{dc}	1
1	1	0	0	$2V_{dc}$	2
1	1	1	0	$3V_{dc}$	3
1	1	1	1	$4V_{dc}$	4

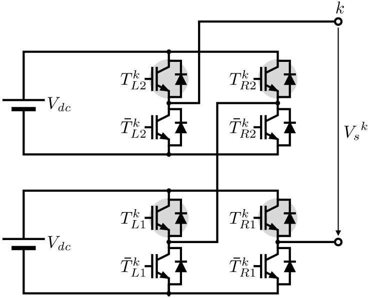
Flying Capacitor Converter



Five-level converter

T_1^k	T_2^k	T_3^k	T_4^k	${V_s}^k$	${v_s}^k$
0	0	0	0	0	0
1	0	0	0	V_{dc}	1
0	1	0	0	V_{dc}	1
0	0	1	0	V_{dc}	1
0	0	0	1	V_{dc}	1
1	1	0	0	$2V_{dc}$	2
1	0	1	0	$2V_{dc}$	2
1	0	0	1	$2V_{dc}$	2
0	1	1	0	$2V_{dc}$	2
0	1	0	1	$2V_{dc}$	2
0	0	1	1	$2V_{dc}$	2
1	1	1	0	$3V_{dc}$	3
1	1	0	1	$3V_{dc}$	3
1	0	1	1	$3V_{dc}$	3
0	1	1	1	$3V_{dc}$	3
1	1	1	1	$4V_{dc}$	4

Cascaded Full-Bridge Converter



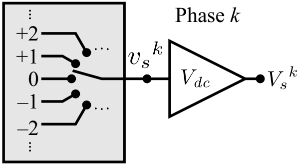
Five-level converter
(Two cells)

T_{L1}^k	T_{L2}^k	T_{R1}^k	T_{R2}^k	$V_s{}^k$	$v_s{}^k$
0	0	1	1	$-2V_{dc}$	-2
1	0	1	1	$-V_{dc}$	-1
0	1	1	1	$-V_{dc}$	-1
0	0	0	1	$-V_{dc}$	-1
0	0	1	0	$-V_{dc}$	-1
1	1	1	1	0	0
1	0	0	1	0	0
1	0	1	0	0	0
0	1	0	1	0	0
0	1	1	0	0	0
0	0	0	0	0	0
1	1	0	1	V_{dc}	1
1	1	1	0	V_{dc}	1
1	0	0	0	V_{dc}	1
0	1	0	0	V_{dc}	1
1	1	1	0	$2V_{dc}$	2

Number of Redundant Switching States

	Output voltage $V_s{}^k$	Number of redundant states $R_d(v_s{}^k)$
Diode clamped	$v_s{}^k V_{dc}$	1
Flying capacitor	$v_s{}^k V_{dc}$	$\dfrac{(N^k-1)!}{(N^k-v_s{}^k-1)!\ v_s{}^k!}$
Cascaded full-bridge	$v_s{}^k V_{dc}$	$\dfrac{(2B^k)!}{(B^k-v_s{}^k)!\ (B^k+v_s{}^k)!}$

Functional diagram



$V_s{}^k =$ Output voltage
$v_s{}^k =$ Output level
$V_{dc} =$ Voltage step
$N^k =$ Number of levels
$B^k =$ Number of cells

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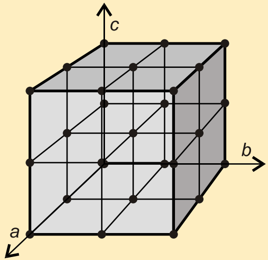
Outline

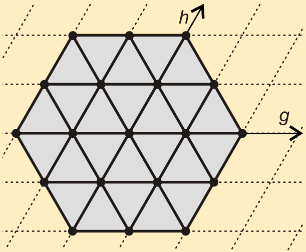
Compared Space Vector PWM Algorithms

3D SVPWM algorithm



by Prats et al. [81]

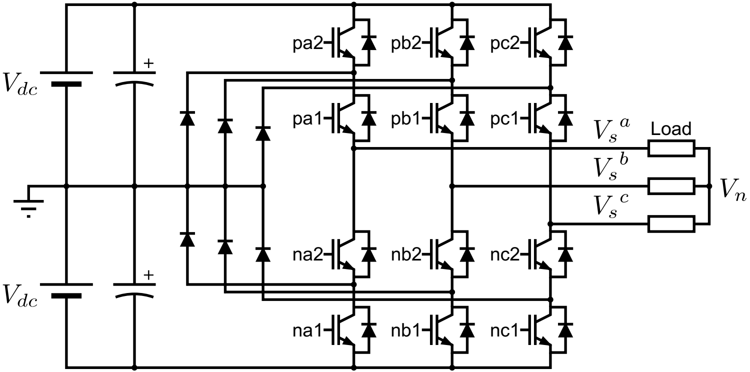
2D SVPWM algorithm



by Celanovic et al. [72]

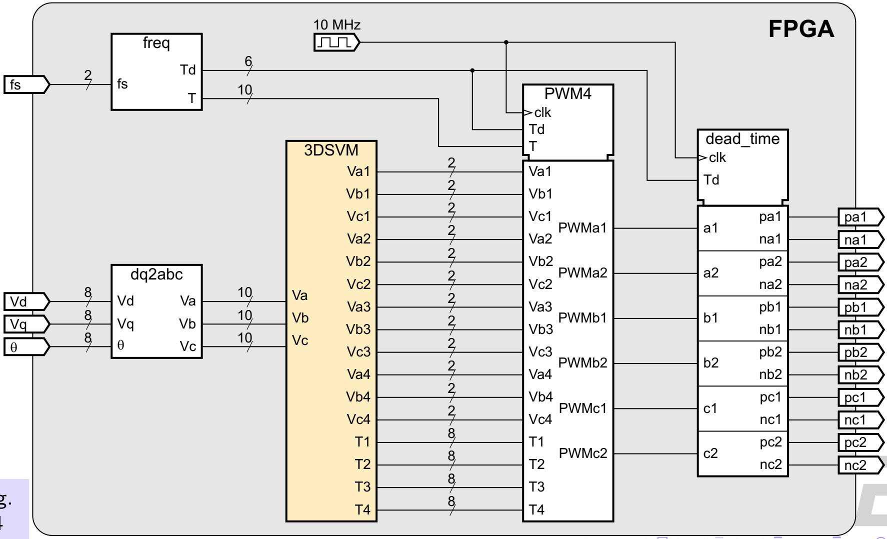
- Any number of levels
- $V_s = v_s V_{dc}, \quad v_s \in \mathbb{Z}$ ▷ Standard multilevel topologies
- Low computational cost

Neutral-Point Clamped Inverter

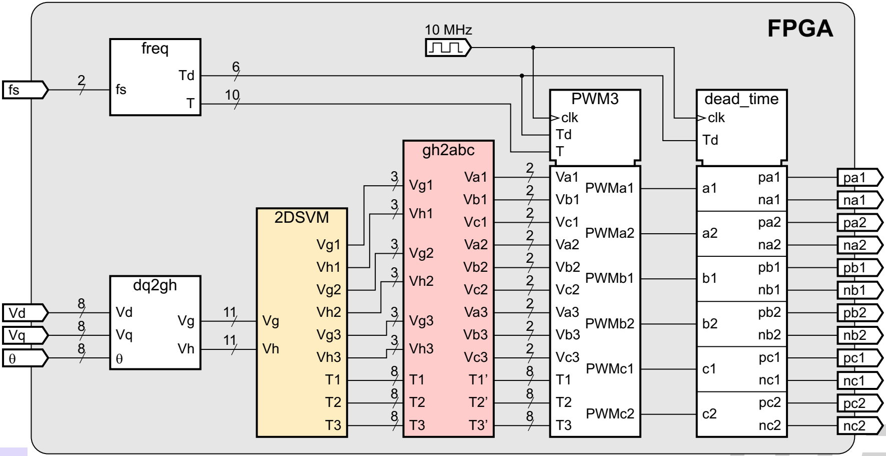


- Described in VHDL
- Implemented in a FPGA

Implementation of the 3D SVPWM Algorithm

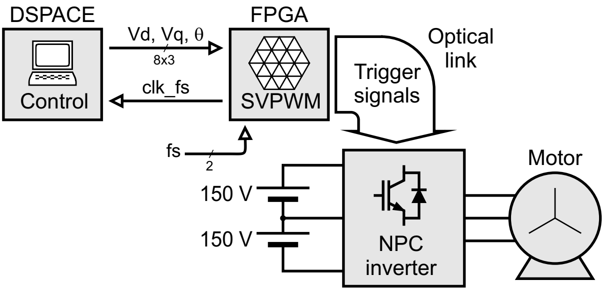


Implementation of the 2D SVPWM Algorithm



Experimental Setup

Diagram



- DSPACE DS1103 PPC Controller Board.
- XC3S200 FPGA.
- Three-phase three-level neutral point clamped inverter.
- Three-phase induction motor with floating neutral.

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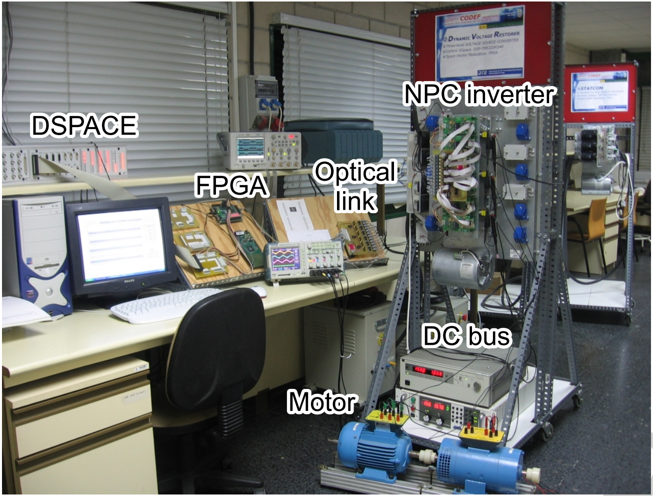
Experimental Setup
Photograph

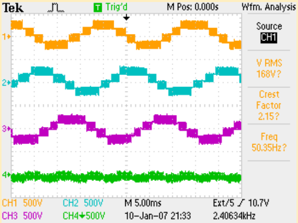


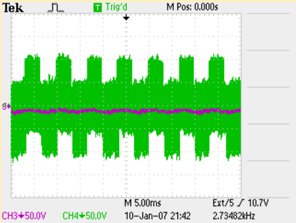
Measurements

Sinusoidal Reference

3D SVPWM

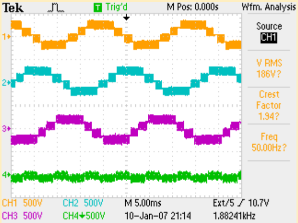
Ch1: $V_s{}^a - V_s{}^b$
Ch2: $V_s{}^b - V_s{}^c$
Ch3: $V_s{}^c - V_s{}^a$
Ch4: V_n

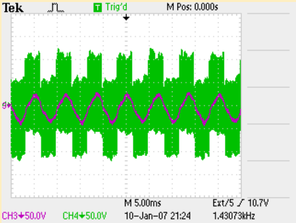




2D SVPWM

Ch1: $V_s{}^a - V_s{}^b$
Ch2: $V_s{}^b - V_s{}^c$
Ch3: $V_s{}^c - V_s{}^a$
Ch4: V_n





Algorithms Comparison

3D SVPWM algorithm

- Does not take advantage of joint-phase redundancy
- Floating and grounded neutral
- Modulation index $[0, 1]$
- Sorted switching vector sequence
- Low computational cost
- Easy to implement

2D SVPWM algorithm

- Takes advantage of joint-phase redundancy
- Floating neutral
- Modulation index $[0, 1.15]$
- Unsorted space vector sequence
- Difficult to find switching vector sequence from space vector sequence

Without-redundancy SVPWM problem ▷ Unique solution
With-redundancy SVPWM problem ▷ Multiple solutions

Algorithms Comparison

3D SVPWM algorithm

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Without-redundancy SVPWM problem ▷ Unique solution
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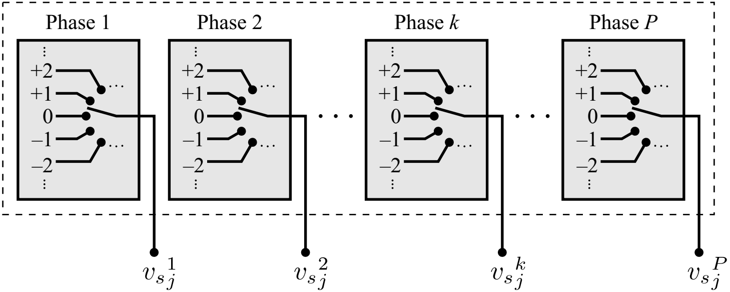
Outline

P-Phase SVPWM Formulation

Multilevel multiphase converter:



Formulation in a P-dimensional space:

$$\mathbf{v}_r = [v_r^{1}, v_r^{2}, \ldots, v_r^{P}]^{\mathrm{T}} \in \mathbb{R}^P$$

$$\mathbf{v}_{sj} = [v_{sj}^{1}, v_{sj}^{2}, \ldots, v_{sj}^{P}]^{\mathrm{T}} \in \mathbb{Z}^P$$

Modulation Law

$$\mathbf{v}_r = \sum_{j=1}^{P+1} \mathbf{v}_{sj} t_j, \qquad \text{where} \sum_{j=1}^{P+1} t_j = 1$$

Matrix formulation

$$\begin{bmatrix} 1 \\ v_r^1 \\ v_r^2 \\ \vdots \\ v_r^P \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 1 & \dots & 1 \\ v_{s_1}^1 & v_{s_2}^1 & \dots & v_{s_{P+1}}^1 \\ v_{s_1}^2 & v_{s_2}^2 & \dots & v_{s_{P+1}}^2 \\ \vdots & \vdots & \ddots & \vdots \\ v_{s_1}^P & v_{s_2}^P & \dots & v_{s_{P+1}}^P \end{bmatrix}}_{\text{Unknown!}} \begin{bmatrix} t_1 \\ t_2 \\ \vdots \\ t_{P+1} \end{bmatrix}$$

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Modulation Law

$$\mathbf{v}_r = \sum_{j=1}^{P+1} \mathbf{v}_{sj} t_j, \qquad \text{where} \sum_{j=1}^{P+1} t_j = 1$$

Matrix formulation

$$\begin{bmatrix} 1 \\ {v_r}^1 \\ {v_r}^2 \\ \vdots \\ {v_r}^P \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 1 & \dots & 1 \\ {v_s}_1^1 & {v_s}_2^1 & \dots & {v_s}_{P+1}^1 \\ {v_s}_1^2 & {v_s}_2^2 & \dots & {v_s}_{P+1}^2 \\ \vdots & \vdots & \ddots & \vdots \\ {v_s}_1^P & {v_s}_2^P & \dots & {v_s}_{P+1}^P \end{bmatrix}}_{\text{Unknown!}} \begin{bmatrix} t_1 \\ t_2 \\ \vdots \\ t_{P+1} \end{bmatrix}$$

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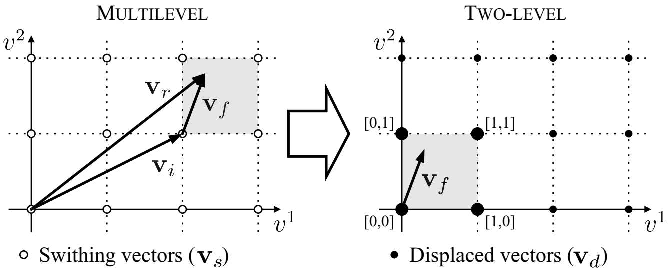
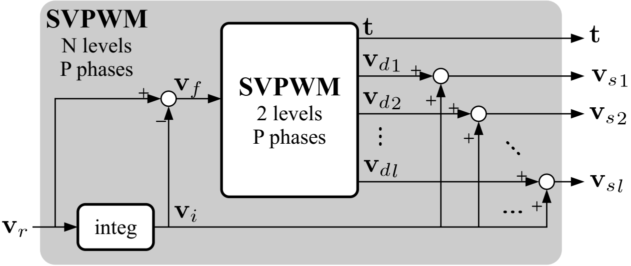
Decomposition



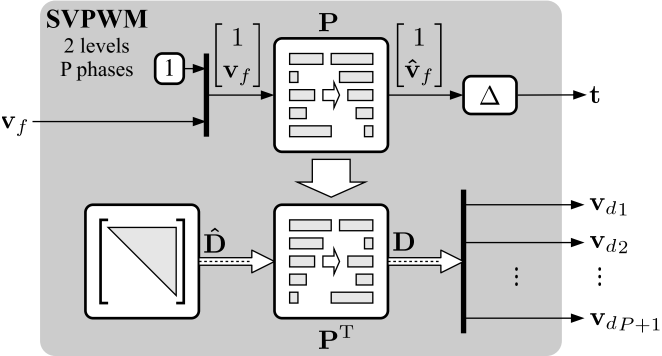
Multilevel multiphase SVPWM	=	Displacement	+	Two-level multiphase SVPWM

Displacement



$\mathbf{v}_i = \mathrm{integ}(\mathbf{v}_r) \in \mathbb{Z}^P$	Integer part of the reference
$\mathbf{v}_f = \mathbf{v}_r - \mathbf{v}_i \in \mathbb{R}^P$	Fractional part of the reference
$\mathbf{v}_{dj} = f(\mathbf{v}_f)$	Displaced switching vector sequence
$t_j = f(\mathbf{v}_f)$	Switching times
$\mathbf{v}_{sj} = \mathbf{v}_i + \mathbf{v}_{dj} \in \mathbb{Z}^P$	Switching vector sequence

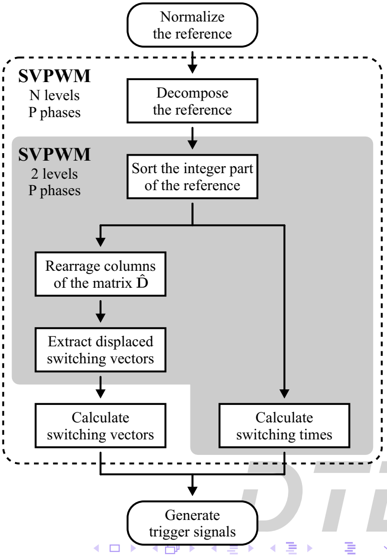
Two-Level SVPWM



$\mathbf{P} = f(\mathbf{v}_f)$	Permutation matrix → Sort components of $\mathbf{v}_f$
$\mathbf{D} = \mathbf{P}^{\mathrm{T}}\hat{\mathbf{D}}$	Displaced switching vectors
$\hat{\mathbf{D}} =$ (constant)	Upper triangular matrix made with ones
$t_j = \hat{v}_f{}^{j-1} - \hat{v}_f{}^{j}$	Switching times

Algorithm Step List

0. Normalize the reference $\mathbf{v}_r$
1. Decompose the normalized reference into its integer part $\mathbf{v}_i$ and its fractional part $\mathbf{v}_f$
2. Calculate the permutation matrix $\mathbf{P}$
3. Calculate the matrix $\mathbf{D}$
4. Extract the displaced switching vectors $\mathbf{v}_{dj}$ from matrix $\mathbf{D}$
5. Obtain the final switching vectors $\mathbf{v}_{sj}$
6. Calculate the switching times t_j



Algorithm Features

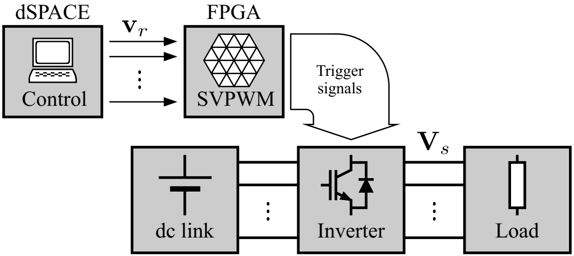
- Valid for the standard multilevel topologies.
- Any number of levels.
- Any number of phases.
- Sorted switching vector sequence ▷ Minimizes number of switchings.
- Low computational complexity ▷ Real-time implementation.
- Modulation index range:

$$0 \leq \frac{V_{\text{fund}}}{V_{dc}} \leq \frac{N-1}{2}$$

- Does not takes advantage of joint-phase redundancy.
- For converters with and without floating neutral.

Experimental Setup

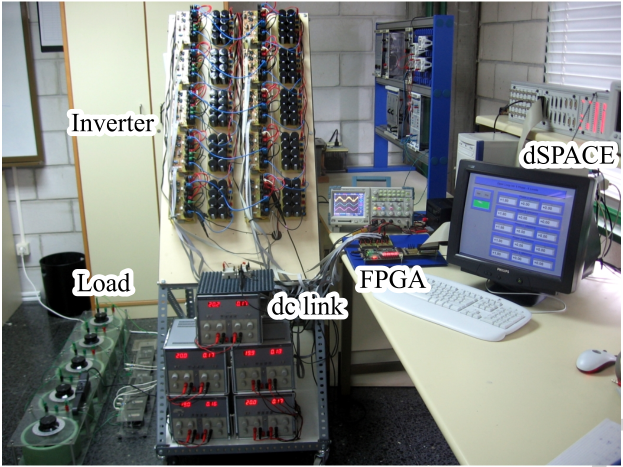
Diagram



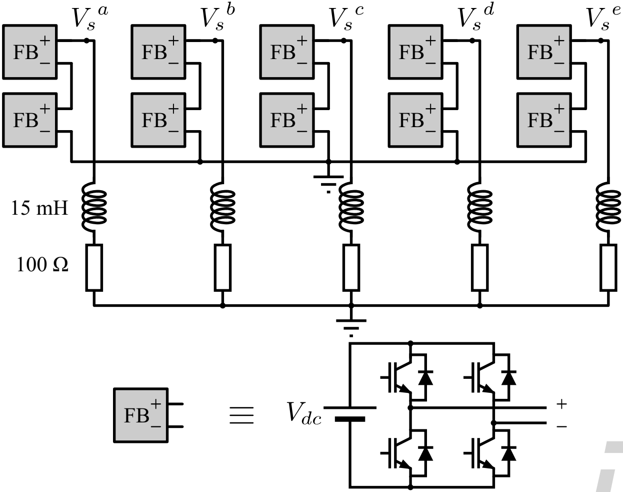
- DSPACE DS1103 PPC Controller Board
- XC3S200 FPGA
- Five-level five-phase cascaded full-bridge inverter
- RL load with grounded neutral

Experimental Setup

Photograph

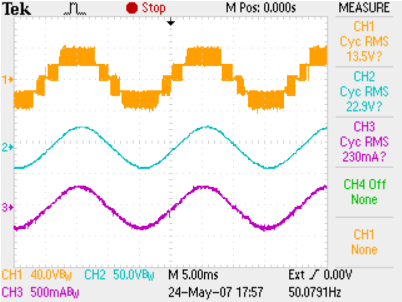


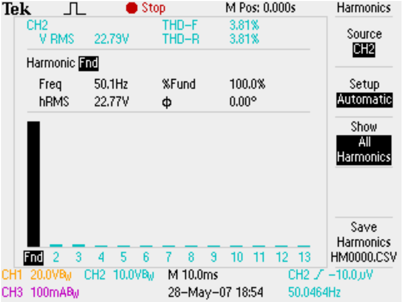
Five-Level Five-Phase Inverter



Experimental Measurements

Pure Sinusoidal Reference



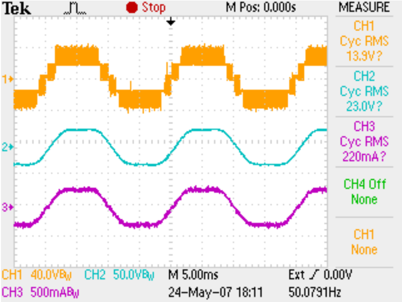


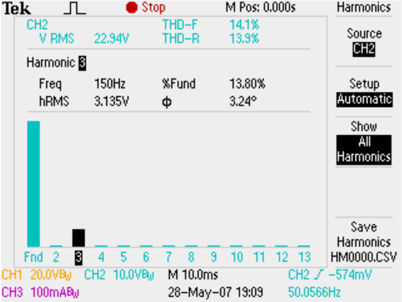
- Switching frequency: $10\,\mathrm{kHz}$
- Fundamental frequency: $50\,\mathrm{Hz}$
- Fundamental amplitude: $A_1 = 1.8V_{dc}$

Ch1: Leg voltage ${V_s}^a$
Ch2: Filtered leg voltage ${V_s}^a$
Ch3: Leg current ${I_s}^a$

Experimental Measurements

Pure Sinusoidal Reference With Third Harmonic Injection





- Switching frequency: $10\,\mathrm{kHz}$
- Fundamental frequency: $50\,\mathrm{Hz}$
- Fundamental amplitude: $A_1 = 1.8V_{dc}$
- Third harmonic amplitude: $A_3 = 0.3V_{dc}$

Ch1: Leg voltage ${V_s}^a$
Ch2: Filtered leg voltage ${V_s}^a$
Ch3: Leg current ${I_s}^a$

Application to Three-Phase Converters

General technique ▷ Can be used with three-phase converters

Three-leg converters:

- $P = 3$
- Same as the 3D SVPWM algorithm by Prats et al. [81]

Four-leg converters:

- $P = 4$
- New four-dimensional SVPWM algorithm

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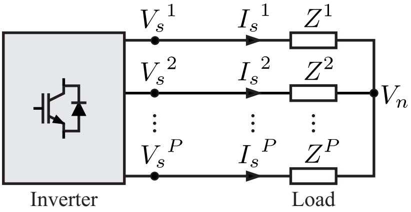
Outline

Multiphase System With Floating Neutral



Phase current:

$$I_s{}^k = \frac{\tilde{V}_s{}^k}{Z^k} - \frac{\sum_{i=1}^{P} \tilde{V}_s{}^i / Z^i}{\sum_{i=1}^{P} Z^k / Z^i}, \qquad k = 1, 2, \ldots, P$$

Non-homopolar component of the output voltage:

$$\tilde{V}_s{}^k = V_s{}^k - \frac{V_s{}^1 + V_s{}^2 + \cdots + V_s{}^P}{P}$$

Modulation Law

$$\tilde{\mathbf{v}}_r = \sum_{j=1}^{l} \tilde{\mathbf{v}}_{sj} t_j, \qquad \text{where } \sum_{j=1}^{l} t_j = 1$$

Matrix formulation

$$\begin{bmatrix} 1 \\ \tilde{v}_r^{\,1} \\ \tilde{v}_r^{\,2} \\ \vdots \\ \tilde{v}_r^{\,P} \end{bmatrix} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ \tilde{v}_{s1}^{\,1} & \tilde{v}_{s2}^{\,1} & \dots & \tilde{v}_{sl}^{\,1} \\ \tilde{v}_{s1}^{\,2} & \tilde{v}_{s2}^{\,2} & \dots & \tilde{v}_{sl}^{\,2} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{v}_{s1}^{\,P} & \tilde{v}_{s2}^{\,P} & \dots & \tilde{v}_{sl}^{\,P} \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ \vdots \\ t_l \end{bmatrix}$$

$\tilde{v}_{s_j}^{k} \in \mathbb{R}$ ▷ Previous SVPWM method cannot be applied

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Modulation Law

$$\tilde{\mathbf{v}}_r = \sum_{j=1}^{l} \tilde{\mathbf{v}}_{sj} t_j, \qquad \text{where } \sum_{j=1}^{l} t_j = 1$$

Matrix formulation

$$\begin{bmatrix} 1 \\ \tilde{v}_r{}^1 \\ \tilde{v}_r{}^2 \\ \vdots \\ \tilde{v}_r{}^P \end{bmatrix} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ \tilde{v}_{s1}^{1} & \tilde{v}_{s2}^{1} & \dots & \tilde{v}_{sl}^{1} \\ \tilde{v}_{s1}^{2} & \tilde{v}_{s2}^{2} & \dots & \tilde{v}_{sl}^{2} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{v}_{s1}^{P} & \tilde{v}_{s2}^{P} & \dots & \tilde{v}_{sl}^{P} \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ \vdots \\ t_l \end{bmatrix}$$

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$\tilde{v}_{sj}^{k} \in \mathbb{R} \triangleright$ Previous SVPWM method cannot be applied

Equivalent Modulation Law

Non-homopolar component

Projection onto the plane

$$\tilde{\pi} : {v_s}^1 + \cdots + {v_s}^P = 0$$

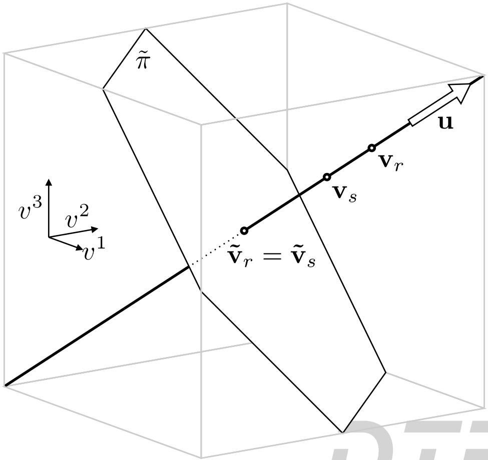
along the vector

$$\mathbf{u} = [1, 1, \ldots, 1]^{\mathrm{T}}$$

Equivalent modulation law

New projection plane

$$\breve{\pi} : {v_s}^P = 0$$



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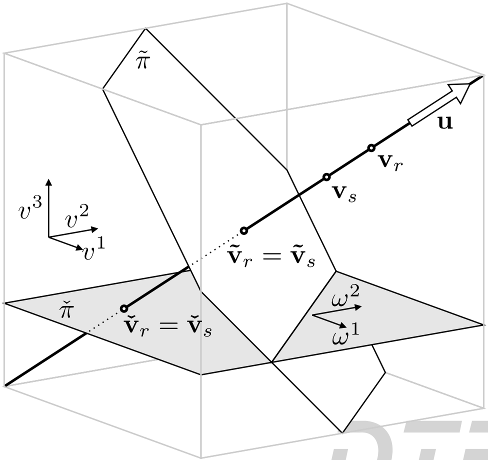

Equivalent Modulation Law

Space vectors: ${\omega_r}^k = {v_r}^k - {v_r}^P \qquad {\omega_s}_j^k = {v_s}_j^k - {v_s}_j^P$

$$\boldsymbol{\omega}_r = \sum_{j=1}^{P} \boldsymbol{\omega}_{sj}\tau_j, \qquad \text{where } \sum_{j=1}^{P} \tau_j = 1$$

Matrix formulation

$$\begin{bmatrix} 1 \\ {\omega_r}^1 \\ {\omega_r}^2 \\ \vdots \\ {\omega_r}^{P-1} \end{bmatrix} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ {\omega_s}_1^1 & {\omega_s}_2^1 & \cdots & {\omega_s}_P^1 \\ {\omega_s}_1^2 & {\omega_s}_2^2 & \cdots & {\omega_s}_P^2 \\ \vdots & \vdots & \ddots & \vdots \\ {\omega_s}_1^{P-1} & {\omega_s}_2^{P-1} & \cdots & {\omega_s}_P^{P-1} \end{bmatrix} \begin{bmatrix} \tau_1 \\ \tau_2 \\ \vdots \\ \tau_P \end{bmatrix}$$

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${\omega_s}_j^k \in \mathbb{Z}$ ▷ Previous SVPWM method can be applied

Equivalent Modulation Law

Space vectors: ${\omega_r}^k = {v_r}^k - {v_r}^P \qquad {\omega_s}_j^k = {v_s}_j^k - {v_s}_j^P$

$$\boldsymbol{\omega}_r = \sum_{j=1}^{P} \boldsymbol{\omega}_{sj}\tau_j, \qquad \text{where } \sum_{j=1}^{P} \tau_j = 1$$

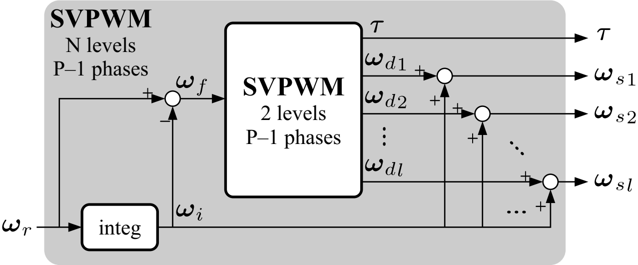
Matrix formulation

$$\begin{bmatrix} 1 \\ {\omega_r}^1 \\ {\omega_r}^2 \\ \vdots \\ {\omega_r}^{P-1} \end{bmatrix} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ {\omega_s}_1^1 & {\omega_s}_2^1 & \dots & {\omega_s}_P^1 \\ {\omega_s}_1^2 & {\omega_s}_2^2 & \dots & {\omega_s}_P^2 \\ \vdots & \vdots & \ddots & \vdots \\ {\omega_s}_1^{P-1} & {\omega_s}_2^{P-1} & \dots & {\omega_s}_P^{P-1} \end{bmatrix} \begin{bmatrix} \tau_1 \\ \tau_2 \\ \vdots \\ \tau_P \end{bmatrix}$$

${\omega_s}_j^k \in \mathbb{Z} \triangleright$ Previous SVPWM method can be applied

Space Vector Sequence

SVPWM algorithm without redundancy:



Output: Space vector sequence + Dwell times

$$\boldsymbol{\omega}_{sj} = \boldsymbol{\omega}_i + \boldsymbol{\omega}_{dj} \quad \rightarrow \quad \tau_j$$

Translation into: Switching vectors + Switching times

$$\mathbf{v}_{sj} = \mathbf{T_v}\boldsymbol{\omega}_{sj} + n\mathbf{u} \quad \rightarrow \quad t_j$$

Joint-Phase Redundancy

$$\mathbf{v}_s(n, j) = \mathbf{T_v}\boldsymbol{\omega}_{dj} + n\mathbf{u}$$

Switching vectors arranged in a table:

$\boxed{P = 5}$	$j = 1$ $\boldsymbol{\omega}_{s1}$	$j = 2$ $\boldsymbol{\omega}_{s2}$	$j = 3$ $\boldsymbol{\omega}_{s3}$	$j = 4$ $\boldsymbol{\omega}_{s4}$	$j = 5$ $\boldsymbol{\omega}_{s5}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$n = 4$	$\mathbf{v}_s(4, 1)$	$\mathbf{v}_s(4, 2)$	$\mathbf{v}_s(4, 3)$	$\mathbf{v}_s(4, 4)$	$\mathbf{v}_s(4, 5)$
$n = 3$	$\mathbf{v}_s(3, 1)$	$\mathbf{v}_s(3, 2)$	$\mathbf{v}_s(3, 3)$	$\mathbf{v}_s(3, 4)$	$\mathbf{v}_s(3, 5)$
$n = 2$	$\mathbf{v}_s(2, 1)$	$\mathbf{v}_s(2, 2)$	$\mathbf{v}_s(2, 3)$	$\mathbf{v}_s(2, 4)$	$\mathbf{v}_s(2, 5)$
$n = 1$	$\mathbf{v}_s(1, 1)$	$\mathbf{v}_s(1, 2)$	$\mathbf{v}_s(1, 3)$	$\mathbf{v}_s(1, 4)$	$\mathbf{v}_s(1, 5)$
$n = 0$	$\mathbf{v}_s(0, 1)$	$\mathbf{v}_s(0, 2)$	$\mathbf{v}_s(0, 3)$	$\mathbf{v}_s(0, 4)$	$\mathbf{v}_s(0, 5)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

- At least one vector must be selected from each column
- Minimize switching losses ▷ Sequence with adjacent vectors

Selection of Switching Vectors

Adjacent vectors string

Select P consecutive switching vectors in the string

New q index:

$$q = \sum_{k=1}^{P} {v_s}_j^k$$

Boundaries:

$$q_{\min} = f(N_{\min})$$

$$q_{\max} = f(N_{\max})$$

$$
\begin{array}{ccl}
n & j & \mathbf{v}_s(n,j) \\
\vdots & \vdots & \quad\vdots \\
3 & 3 & \mathbf{v}_s(3,3) = [\ \ 2,4,3,5,2]^T \\
3 & 2 & \mathbf{v}_s(3,2) = [\ \ 1,4,3,5,2]^T \\
3 & 1 & \mathbf{v}_s(3,1) = [\ \ 1,4,3,4,2]^T \\
2 & 5 & \mathbf{v}_s(2,5) = [\ \ 1,4,2,4,2]^T \\
2 & 4 & \mathbf{v}_s(2,4) = [\ \ 1,3,2,4,2]^T \\
2 & 3 & \mathbf{v}_s(2,3) = [\ \ 1,3,2,4,1]^T \\
2 & 2 & \mathbf{v}_s(2,2) = [\ \ 0,3,2,4,1]^T \\
2 & 1 & \mathbf{v}_s(2,1) = [\ \ 0,3,2,3,1]^T \\
1 & 5 & \mathbf{v}_s(1,5) = [\ \ 0,3,1,3,1]^T \\
1 & 4 & \mathbf{v}_s(1,4) = [\ \ 0,2,1,3,1]^T \\
1 & 3 & \mathbf{v}_s(1,3) = [\ \ 0,2,1,3,0]^T \\
1 & 2 & \mathbf{v}_s(1,2) = [-1,2,1,3,0]^T \\
\vdots & \vdots & \quad\vdots
\end{array}
$$

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Selection of Switching Vectors

Adjacent vectors string

Select P consecutive switching vectors in the string

New q index:

$$q = \sum_{k=1}^{P} v_{s_j}^{k}$$

Boundaries:

$$q_{\min} = f(N_{\min})$$

$$q_{\max} = f(N_{\max})$$

n	j	$\mathbf{v}_s(n,j)$
$\vdots$	$\vdots$	$\vdots$
3	3	$\mathbf{v}_s(3,3) = [\ \ 2,4,3,5,2]^{\mathrm{T}}$
3	2	$\mathbf{v}_s(3,2) = [\ \ 1,4,3,5,2]^{\mathrm{T}}$
3	1	$\mathbf{v}_s(3,1) = [\ \ 1,4,3,4,2]^{\mathrm{T}}$
2	5	$\mathbf{v}_s(2,5) = [\ \ 1,4,2,4,2]^{\mathrm{T}}$
2	4	$\mathbf{v}_s(2,4) = [\ \ 1,3,2,4,2]^{\mathrm{T}}$
2	3	$\mathbf{v}_s(2,3) = [\ \ 1,3,2,4,1]^{\mathrm{T}}$
2	2	$\mathbf{v}_s(2,2) = [\ \ 0,3,2,4,1]^{\mathrm{T}}$
2	1	$\mathbf{v}_s(2,1) = [\ \ 0,3,2,3,1]^{\mathrm{T}}$
1	5	$\mathbf{v}_s(1,5) = [\ \ 0,3,1,3,1]^{\mathrm{T}}$
1	4	$\mathbf{v}_s(1,4) = [\ \ 0,2,1,3,1]^{\mathrm{T}}$
1	3	$\mathbf{v}_s(1,3) = [\ \ 0,2,1,3,0]^{\mathrm{T}}$
1	2	$\mathbf{v}_s(1,2) = [-1,2,1,3,0]^{\mathrm{T}}$
$\vdots$	$\vdots$	$\vdots$

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Selection of Switching Vectors

Adjacent vectors string

Select P consecutive switching vectors in the string

New q index:

$$q = \sum_{k=1}^{P} v_{s_j}^{k}$$

Boundaries:

$$q_{\min} = f(N_{\min})$$

$$q_{\max} = f(N_{\max})$$

n	j	$\mathbf{v}_s(n,j)$
$\vdots$	$\vdots$	$\vdots$
3	3	$\mathbf{v}_s(3,3) = [\ 2,4,3,5,2]^{\mathrm{T}}$
3	2	$\mathbf{v}_s(3,2) = [\ 1,4,3,5,2]^{\mathrm{T}}$
3	1	$\mathbf{v}_s(3,1) = [\ 1,4,3,4,2]^{\mathrm{T}}$
2	5	$\mathbf{v}_s(2,5) = [\ 1,4,2,4,2]^{\mathrm{T}}$
2	4	$\mathbf{v}_s(2,4) = [\ 1,3,2,4,2]^{\mathrm{T}}$
2	3	$\mathbf{v}_s(2,3) = [\ 1,3,2,4,1]^{\mathrm{T}}$
2	2	$\mathbf{v}_s(2,2) = [\ 0,3,2,4,1]^{\mathrm{T}}$
2	1	$\mathbf{v}_s(2,1) = [\ 0,3,2,3,1]^{\mathrm{T}}$
1	5	$\mathbf{v}_s(1,5) = [\ 0,3,1,3,1]^{\mathrm{T}}$
1	4	$\mathbf{v}_s(1,4) = [\ 0,2,1,3,1]^{\mathrm{T}}$
1	3	$\mathbf{v}_s(1,3) = [\ 0,2,1,3,0]^{\mathrm{T}}$
1	2	$\mathbf{v}_s(1,2) = [-1,2,1,3,0]^{\mathrm{T}}$
$\vdots$	$\vdots$	$\vdots$

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Selection of Switching Vectors

Adjacent vectors string

Select P consecutive switching vectors in the string

New q index:

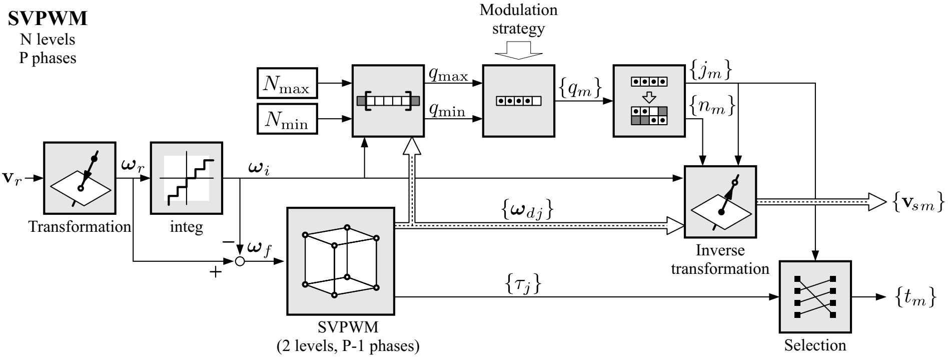
$$q = \sum_{k=1}^{P} v_{s_j}^{k}$$

Boundaries:

$$q_{\min} = f(N_{\min})$$
$$q_{\max} = f(N_{\max})$$

q	n	j	$\mathbf{v}_s(n,j)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$
16	3	3	$\mathbf{v}_s(3,3) = [2,4,3,5,2]^T$
15	3	2	$\mathbf{v}_s(3,2) = [1,4,3,5,2]^T$
$q_{\max}$=14	3	1	$\mathbf{v}_s(3,1) = [1,4,3,4,2]^T$
13	2	5	$\mathbf{v}_s(2,5) = [1,4,2,4,2]^T$
12	2	4	$\mathbf{v}_s(2,4) = [1,3,2,4,2]^T$
11	2	3	$\mathbf{v}_s(2,3) = [1,3,2,4,1]^T$
10	2	2	$\mathbf{v}_s(2,2) = [0,3,2,4,1]^T$
9	2	1	$\mathbf{v}_s(2,1) = [0,3,2,3,1]^T$
8	1	5	$\mathbf{v}_s(1,5) = [0,3,1,3,1]^T$
7	1	4	$\mathbf{v}_s(1,4) = [0,2,1,3,1]^T$
$q_{\min}$= 6	1	3	$\mathbf{v}_s(1,3) = [0,2,1,3,0]^T$
5	1	2	$\mathbf{v}_s(1,2) = [-1,2,1,3,0]^T$
$\vdots$	$\vdots$	$\vdots$	$\vdots$

Block Diagram of the Algorithm



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Algorithm Features

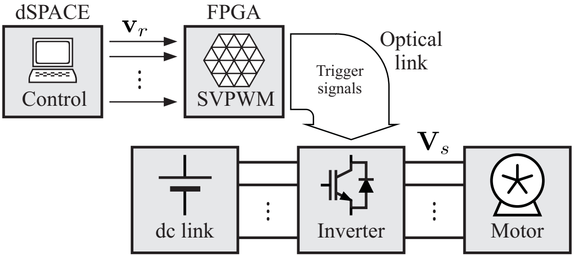
- Valid for the standard multilevel topologies.
- Any number of levels.
- Any number of phases.
- Sorted switching vector sequence ▷ Minimizes number of switchings.
- Low computational complexity ▷ Real-time implementation.
- Modulation index range:

$$0 \leq \frac{V_{\text{fund}}}{V_{dc}} \leq \frac{N-1}{2\cos\frac{\pi}{2P}}$$

- Takes advantage of switching state redundancy.
- For converters with floating neutral.

Experimental Setup

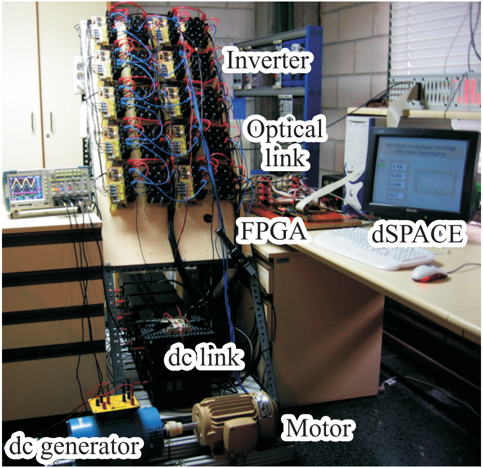
Diagram



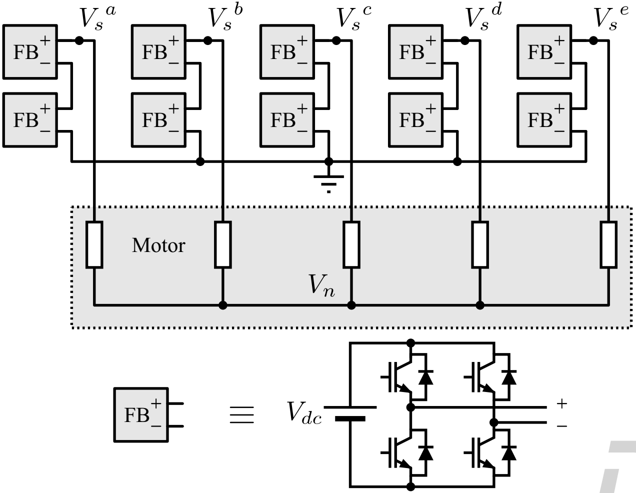
- DSPACE DS1103 PPC Controller Board.
- XC3S200 FPGA.
- Five-level five-phase cascaded full bridge inverter.
- Five-phase induction motor, floating neutral.

Experimental Setup

Photograph

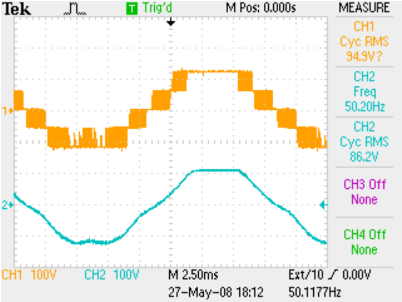


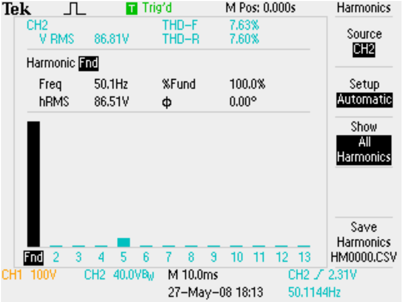
Five-Level Five-Phase Motor Drive



Experimental Measurements

Leg Voltage



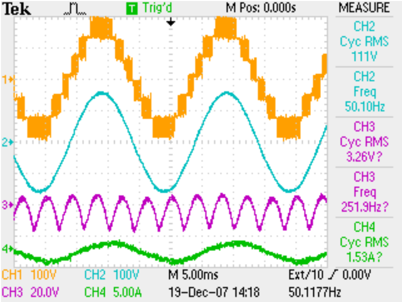


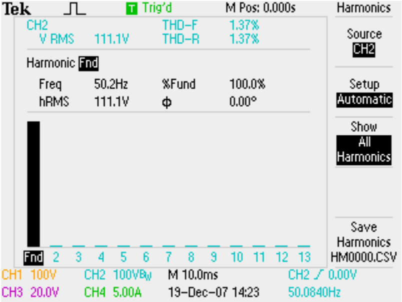
- Switching frequency: $10\,\mathrm{kHz}$
- Fundamental frequency: $50\,\mathrm{Hz}$
- Fundamental amplitude: $A = 2.102V_{dc}$

Ch1: Leg voltage ${V_s}^a$
Ch2: Filtered leg voltage ${V_s}^a$

Experimental Measurements

Phase-to-Phase Voltage





- Switching frequency: $10\,\mathrm{kHz}$
- Fundamental frequency: $50\,\mathrm{Hz}$
- Fundamental amplitude: $A = 2.102 V_{dc}$

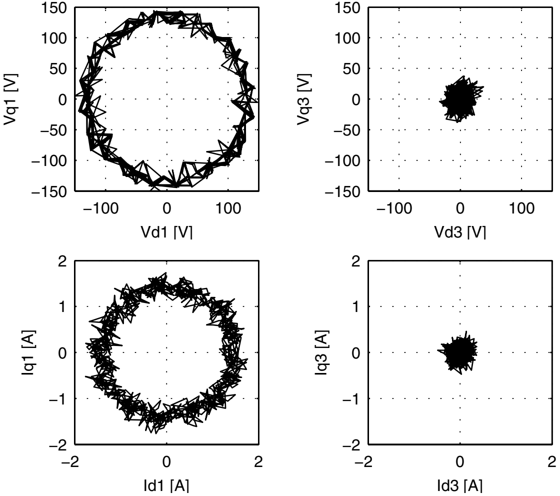
Ch1: Phase-to-phase volt. ${V_s}^a - {V_s}^b$
Ch2: Filtered voltage ${V_s}^a - {V_s}^b$
Ch3: Neutral point voltage V_n
Ch4: Phase current ${I_s}^a$

Experimental Measurements

Trajectories in dq Axes

Voltage

Current



Application to Three-Phase Converters

General technique ▷ Can be used with three-phase converters

Three-leg converters:

- $P = 3$
- Extension of the 2D SVPWM algorithm by Celanovic et al. [72]

Four-leg converters:

- $P = 4$
- Extension of the 3D SVPWM algorithm by Franquelo et al. [89]

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Outline

1. Introduction
2. Per-Phase Redundancy in Multilevel Converters
3. Implementation of Multilevel SVPWM Algorithms
4. Multilevel Multiphase SVPWM Algorithm
5. Multilevel Multiphase SVPWM Algorithm With Switching State Redundancy
6. Conclusions
   - Conclusions
   - Future Research
   - Contributions

Conclusions I

Switching laws and per-phase redundancy in multilevel converters

- Studied for the three standard topologies.
- New expressions to calculate the number of redundant switching states.

Two multilevel three-phase SVPWM algorithms compared and implemented in a FPGA:

- 3D SVPWM algorithm by Prats et al.
- 2D SVPWM algorithm by Celanovic et al.

Conclusions II

Two new multilevel multiphase SVPWM algorithms

- Can be used with the standard multilevel topologies.
- Valid for any number of phases and levels.
- Sorted switching sequence ▷ Minimizes number of switchings.
- Suitable for real-time implementation in low-cost devices.
- Implementation in a FPGA.
- Tested with a 5-level 5-phase cascaded full-bridge inverter.

Conclusions III

SVPWM algorithm without switching state redundancy:

- Not takes into account joint-phase redundancy.
- Converters with and without floating neutral.
- Reduced modulation index range.
- Single solution.

SVPWM algorithm with switching state redundancy:

- Takes advantage of joint-phase redundancy:
- Converters with floating neutral.
- Extend the modulation index range.
- Multiple solutions ▷ Possible to include a modulation strategy.

Future Research

- Particularize for other number of phases.
- Study the spectrum of the output voltage.
- Develop of the switching strategies to be included in the SVPWM with switching state redundancy.
- Extend the SVPWM techniques to the overmodulation region.

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Contributions

Major contribution:

- Development of two algorithms that solve multilevel multiphase SVPWM problem.

Minor contributions:

- Expressions to calculate the number of redundant switching states in standard multilevel topologies.
- Comparative of the hardware implementation of two multilevel three-phase SVPWM algorithms.

Space Vector Pulse-Width Modulation for Multilevel Multiphase Voltage-Source Converters

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9 January 2009

Dissertation submitted for the degree of
European Doctor of Philosophy in Electrical Engineering